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TENSILE PROPERTIES OF TANTALUM AND TUNGSTEN 10-FIBER BUNDLES AT 1000° F (812 K)

by Ruluff D. McIntyre

Lewis Research Center
Cleveland, Ohio

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ABSTRACT

Tensile properties of tantalum and tungsten individual fibers and 10-fiber bundles were studied at 1000° F (812 K). Bundles comprised of both tantalum and tungsten fibers with 20, 50, and 80 percent tungsten fibers were also tested. A statistical study related bundle strengths to single-fiber strengths. Bundles of tungsten fibers were less strong than single fibers tested separately. Bundles of tantalum fibers were as strong as tantalum single fibers. Strength followed the rule of mixtures for bundles containing mixtures of tantalum and tungsten fibers.

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SUMMARY

This investigation studied the tensile properties of tungsten and tantalum 10-fiber bundles and related these properties to single-fiber strength. Bundles of tungsten fibers broke at a mean breaking stress lower than the mean fiber strength as determined by separate tests on individual fibers. Monofilament tantalum fibers showed slightly more elongation than monofilament tungsten fibers. This additional elongation apparently made it possible for tantalum bundle strengths to agree with monofilament tantalum-fiber strength in spite of slight inaccuracies in experimental technique. The mean breaking stress and volume percentage data conformed to the rule of mixtures for bundles containing mixtures of tantalum and tungsten fibers. This study provides a statistical assessment of tantalum- and tungsten-fiber strength and strength variability and relates single-fiber strengths to bundle strengths of single- and double-component tantalum- and tungsten-fiber bundles.

INTRODUCTION

Although the strengths of single filaments can be measured simply, the prediction or measurement of the strength of a number of filaments tested simultaneously as a bundle is not equally simple and straightforward.

Bundle strength properties were studied by several other investigators. Bundle strength can be predicted from the mean monofilament strength and its standard deviation (ref. 1) or from Weibull parameters (ref. 2). Tsai also found that, when the rule of mixtures equation is used to predict the axial strength of mixed-fiber bundles, the strengths of single-component bundles should be used. This will give lower strength limits. Theoretical studies of ideal bundles were done by Daniels, Pierce, Coleman, Rosen, and Rosenbaum (refs. 3 to 7). Little experimental work has been done on bundles.

No work has been done on refractory-metal fiber bundles.

This investigation studied the properties of tungsten and tantalum 10-fiber bundles and related these properties to single-fiber strength. Another objective was to determine a method for predicting the strength of 10-fiber bundles from knowledge of individual fiber strength properties. Still another goal was to evaluate the extent of conformance to the rule of mixtures for bundles containing mixtures of tantalum and tungsten fibers.

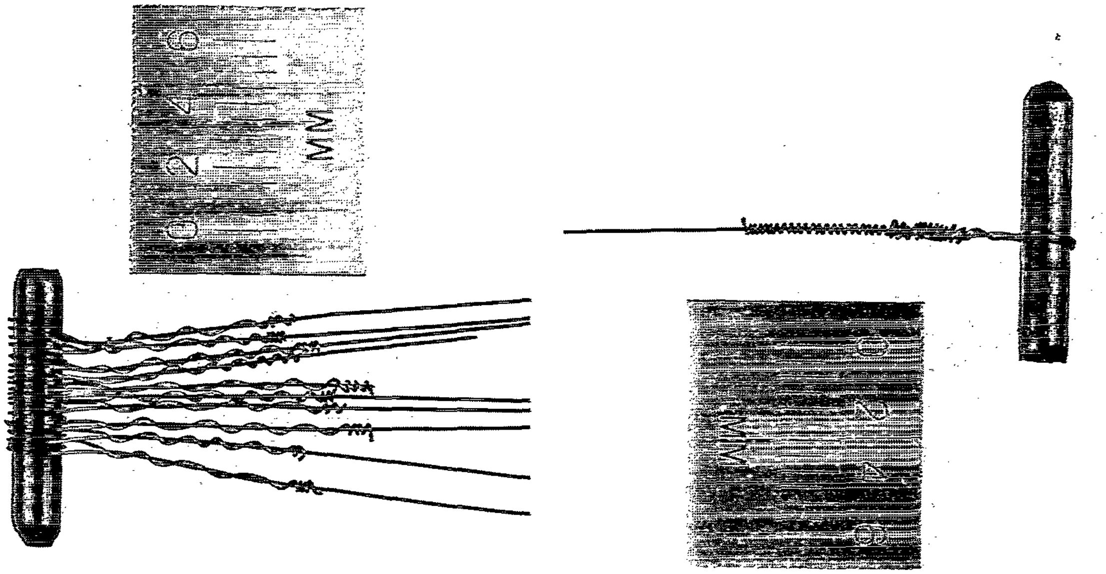
Tantalum-tungsten bundles were tensile tested at 1000° F (812 K) at a crosshead speed of 0.1 inch per minute (0.00004 m/sec) in vacuum. Bundles contained 0, 20, 50, 80, and 100 volume percent tungsten fibers. Single fibers of tantalum and tungsten were also tested. Ten specimens were tested for each type of fiber strength data sought. A statistical analysis of the strength data was performed.

MATERIALS

In the present investigation, the tensile properties of monofilament tantalum and tungsten fibers, bundles of tantalum or tungsten fibers, and bundles with both tantalum and tungsten fibers were measured. The bundles contained 0, 20, 50, 80, and 100 volume percent tungsten where the total number of fibers in each bundle was ten. This number was selected so that it would be easy to observe the first fiber to break in a bundle. With a small number of fibers each fiber carries a sufficiently large fraction of the total load on the bundle so that it is apparent when the first fiber breaks because of the large percentage dropoff in load. All fibers used were 0.005 inch (0.00013 m) in diameter. A typical analysis for the tantalum fiber in weight percent is as follows: carbon, 0.01; oxygen, 0.02; nitrogen, 0.005; hydrogen, 0.001; niobium, 0.02; iron, 0.003; titanium, 0.005; silicon, 0.01; nickel, 0.001; balance, tantalum. For the tungsten fiber, the following analysis is typical: aluminum, 0.001; calcium, 0.001; molybdenum, 0.002; copper, 0.001; balance, tungsten. Silicon, iron, chromium, nickel, manganese, magnesium, tin, cobalt, silver, lead, thorium, and zirconium were all less than 0.001 weight percent in tungsten.

Specimen Fabrication

Tensile specimens of individual wires were prepared by looping the tungsten or tantalum wire ends around 50-mil-diameter (0.0013-m-diam) stainless-steel (type 304) rods which were 0.375 inch (0.00953 m) long. The looping of fibers is shown in figure 1. Breaks within the gage length could be obtained in a 2-inch (0.051-m) gage length if each



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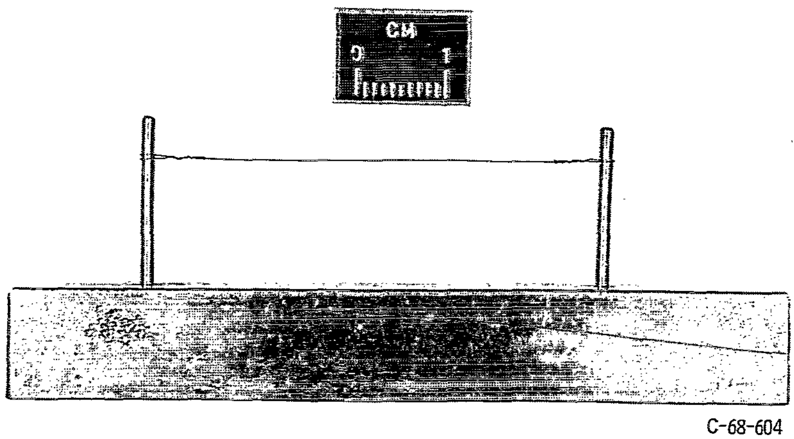
(a) Specimen end fastening.



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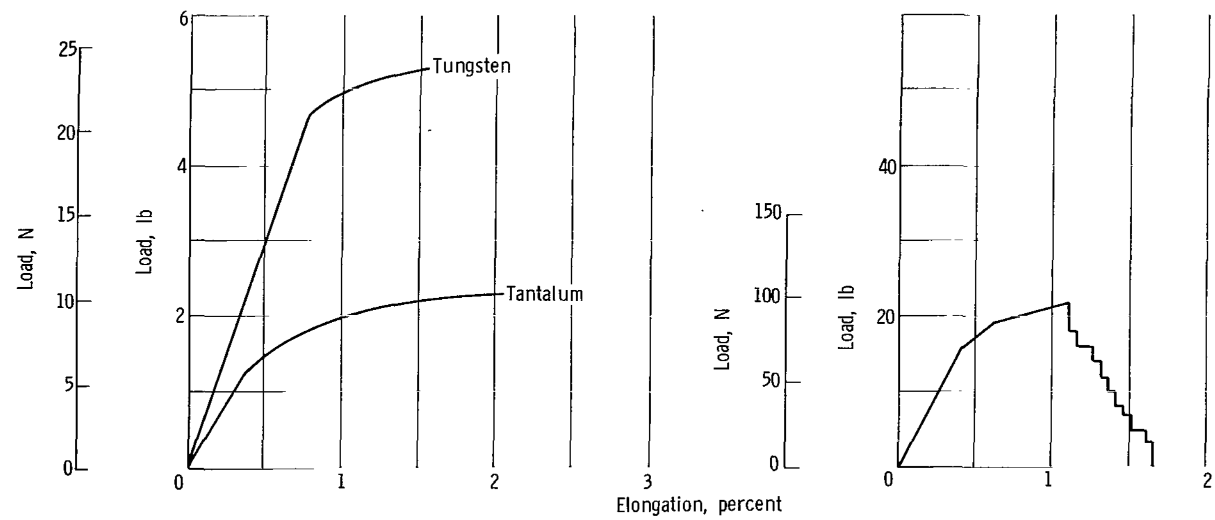
(b) Specimen gage length control jig.

Figure 1. - Fabrication of fiber tensile specimens.

wire were wound around the rods twice before closing the loops. Bundle specimens were fabricated in the same way, in that wires were individually and separately attached to the end support rods by closed loops. Care was exercised by using the jig shown in figure 1(b) in an attempt to obtain identical fiber gage lengths. Fiber gage lengths are believed to be accurate to ±0.002 inch (±0.00005 m). Each bundle was composed of 10 wires, but the number of tantalum or tungsten wires varied in accordance with the volume percentage of tungsten fiber desired. For instance, a 20 volume percent tungsten bundle had two tungsten wires and eight tantalum wires; a 50 volume percent bundle had five tantalum wires and five tungsten wires. Examples of single-fiber and bundle tensile specimens are shown in figure 1.

Mechanical Testing

High-temperature tensile properties at 1000° F (812 K) were investigated by using a tensile-testing machine with a crosshead speed of 0.10 inch per minute (0.00004 m/sec). A 1000° F (812 K) testing temperature, which is above the ductile-brittle transition temperature, was chosen in order to make the tungsten fibers less brittle. Elongation results were obtained from crosshead motion. Fiber test specimens had a 2-inch (0.051-m) gage length, and each wire had a 1.965×10^{-5}-square-inch (1.27×10^{-8}-m^2) cross-sectional area. A 10-fiber bundle would have a total cross-sectional area of 1.96×10^{-4} square inch (1.27×10^{-7} m^2). Tests were conducted in an evacuated chamber (1×10^{-4} torr) (1.33×10^{-2} N/m^2) equipped with quartz heat lamps. Temperatures were measured with a



(a) Single tungsten and single tantalum fibers.

(b) Typical data plot for 10-fiber bundle.

Figure 2. - Load as function of percentage of elongation, at 1000° F (812 K).

platinum - platinum and 13 percent rhodium thermocouple and are estimated to be accurate to ±20° F (16 K). The mean breaking stress for the bundles is defined as the load the bundle supports when the first fiber breaks divided by the total original fiber area. Ten specimens were tested for each type of fiber strength data sought.

It is a feature of the tensile-testing machine used in this study that after a fiber breaks the machine quickly records the reduced load being carried by the remaining fibers (see fig. 2). Thus, after each fiber breaks, a new area and a new strength value can be determined for the bundle composed of the surviving fibers. The process is continued until all fibers are broken.

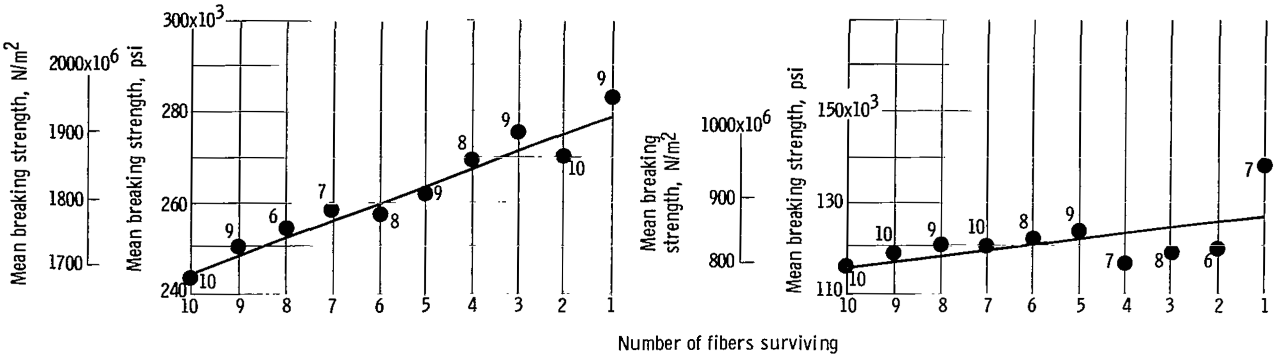
MECHANICAL PROPERTY RESULTS

Tensile Properties

Ultimate tensile strength data for single-fiber and bundle specimens appear in tables I to IV and figure 2. Figure 2(a) shows typical load as a function of percentage of elongation for single tungsten and tantalum wires. Single tantalum wires had approximately 0.5 percent more elongation than single tungsten wires. Load as a function of percentage of elongation for a 10-fiber bundle appears in figure 2(b). Single-component bundles of tungsten fibers broke at a mean breaking strength of 240 000 psi (1655×10^6 N/m^2). This mean strength was taken as the maximum load supported by the bundle divided by the original area. The maximum load was achieved when the first fiber broke.

It would be expected that the mean strength of the 10 bundles would be lower than the mean strength of the individual fibers because the first fiber to fail (the weakest) in the bundle determines the maximum bundle strength. This value of mean breaking strength for the bundle was 11 percent lower than the average strength of 271 000 psi (1868×10^6 N/m^2) obtained for the 10 fibers tested individually. Tantalum-fiber bundles, however, had approximately the same strength as single tantalum fibers, 116 000 psi (800×10^6 N/m^2) for bundles and 119 000 psi (820×10^6 N/m^2) for single fibers.

Tables III and IV give the mean strengths for the all-tungsten- or all-tantalum-fiber bundles based on the loads carried by surviving fibers in a given bundle of fibers after some fibers broke. Strengths as related to the number of fibers surviving were obtained from curves of load as a function of percentage of elongation for tantalum- and tungsten-fiber bundles. These values are shown in tables III and IV and figure 3. Inspection of figure 3(a) indicates an apparent increase in the mean breaking strength per fiber as the number of fibers surviving in tungsten bundles decreases. This relation probably does not hold or is not so prominent for the tantalum bundles. Figure 3(b) shows only a slight



(a) Tungsten bundles. Least-squares line, $y = 283\,000 - 3800x$.

(b) Tantalum bundles. Least-squares line, $y = 128\,000 - 1200x$.

Figure 3. - Mean breaking strength as function of number of fibers surviving for bundles tested at 1000° F (812 K). (Number at each symbol indicates number of data points for which that is the average.)

correlation between mean fiber breaking strength and number of fibers surviving in a bundle.

Tensile Properties Related to Volume Percentage of Tungsten Fibers

The mean breaking strength of 10 bundles of 10 fibers each as a function of the volume percentage of tungsten fibers appears in figure 4. This figure indicates that the mean

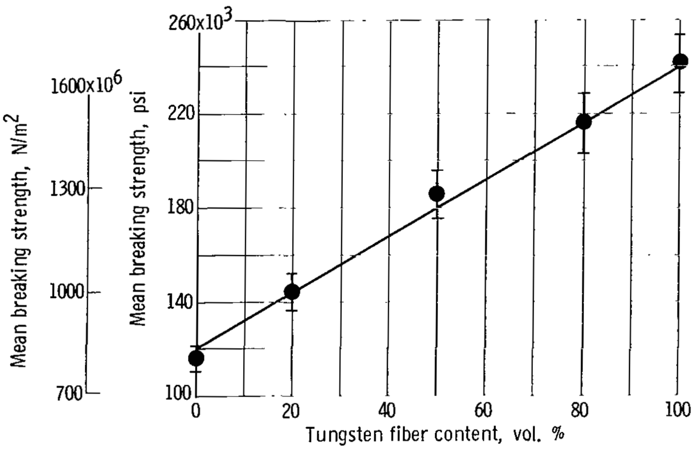


Figure 4. - Mean breaking strength at 1000° F (812 K) of tantalum-tungsten bundles as function of volume percentage of tungsten fibers (10 bundles, 10 fibers each). Ultimate tensile strength = 120 000 + 1210 (vol. %) (least-squares line); mean values and 99.7 percent confidence limits are shown.

breaking strength and volume percentage data conformed to the rule of mixtures for bundles containing mixtures of tantalum and tungsten fibers. Values are shown for the degree of scatter consistent with 99.7 percent confidence limits.

Tensile Properties Related to Percentage of Elongation

Figure 5 suggests there may be a linear relation between the mean breaking strength for single tungsten fibers and the percentage of elongation value when the fiber breaks beyond approximately 0.8 percent elongation. The tungsten fibers showing more elongation at fracture appeared to demonstrate a higher breaking strength. Figure 5 shows that the breaking strength and percentage of elongation at fracture were unrelated for tungsten bundles, single tantalum fibers, or tantalum bundles.

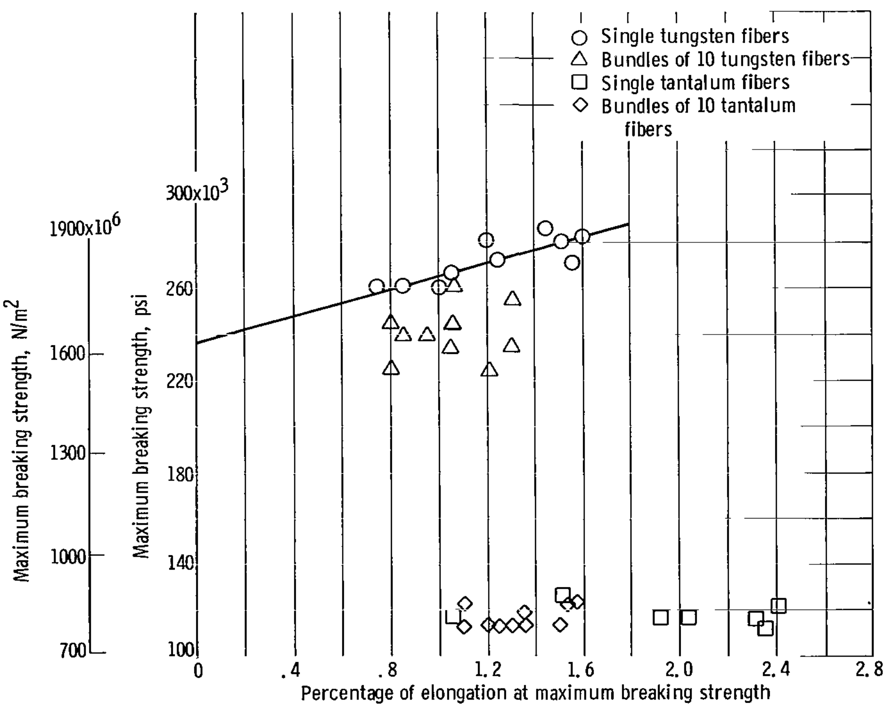


Figure 5. - Maximum breaking strength as function of percentage of elongation for single fibers and bundles of tungsten and tantalum at 1000° F (812 K).

DISCUSSION

The data obtained for tungsten- and tantalum-fiber bundles were compared with values expected from single-fiber data. The data for a bundle of 10 fibers would be expected to be lower than the mean strength of the 10 fibers tested individually since the strength of the 10-fiber bundles was determined by the first fiber to break. If uniform loading is assumed, the first fiber to break should be the weakest in the bundle. Pierce, Daniels, and Rosenbaum (refs. 3, 4, and 7) indicate a lower bound on bundle breaking strength related to the mean strength of the weakest fibers in the bundles. Calculations of ideal bundle behavior appear in appendixes A and B. These calculations show the expected mean breaking strength for classical fiber bundles of tungsten and tantalum fibers based on the known strength distribution for individual fibers. A classical fiber is defined as one that will support a load less than its breaking strength indefinitely without stretching or breaking; however, it will break immediately at a load equal to or greater than its breaking strength (ref. 7). It was calculated that the first fiber of a tungsten-fiber bundle would break at 254 000 psi (1751×10^6 N/m^2) (appendix B). As indicated in the section Tensile Properties, the experimentally observed mean breaking strength for the tungsten-fiber bundles was 240 000 psi (1655×10^6 N/m^2). This strength discrepancy between observed and expected results is probably caused by slight inaccuracies in experimental technique. For example, while gage lengths of fibers were carefully controlled, it was not possible to have them all exactly the same length. Slight differences in gage lengths could lead to slight differences in loading of the individual fibers in a bundle. Nonuniform loading of the fibers would tend to lower the bundle strength values even below those values consistent with the weakest fibers.

No strength discrepancy was evident for the more ductile tantalum fibers (fig. 6). The tantalum-fiber-bundle mean breaking strength was 116 000 psi (800×10^6 N/m^2), which was similar to the mean value obtained from single-fiber data 119 000 psi (820×10^6 N/m^2). The strength predicted in appendix B for the first fiber to break was 112 000 psi (772×10^6 N/m^2). Figure 7 indicates tantalum fibers showed slightly more elongation than tungsten fibers. This additional elongation appeared to be enough to permit tantalum bundle strengths to agree with the expected value from monofilament tantalum-fiber strength in spite of minor inaccuracies in experimental technique. These experimental inaccuracies would include the slight differences in gage length for each fiber when in the bundles. The small improvement in elongation on the part of the tantalum was sufficient to permit failure of the individual fibers in bundles after the onset of plastic flow for all fibers. The more limited ductility of the tungsten fibers resulted in failure at lower elongations before plastic flow began, which would result in some of the fibers not bearing their full share of the load. The slight variation in fiber length apparently resulted in a decrease in strength of the tungsten wire bundles to values even lower than

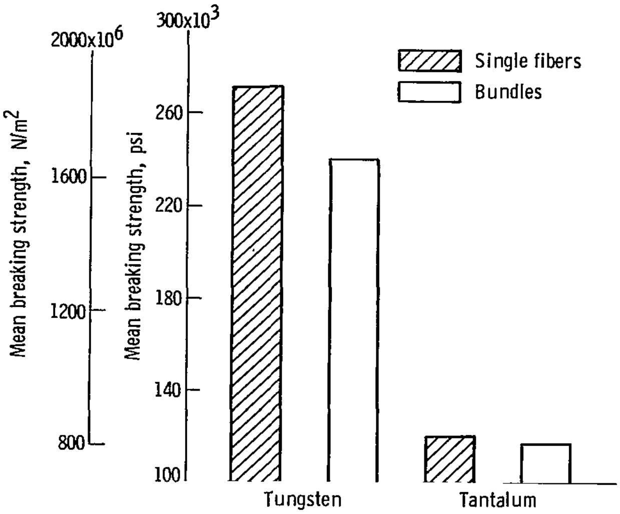


Figure 6. - Comparison of bundle strengths with single-fiber strengths of tungsten and tantalum.

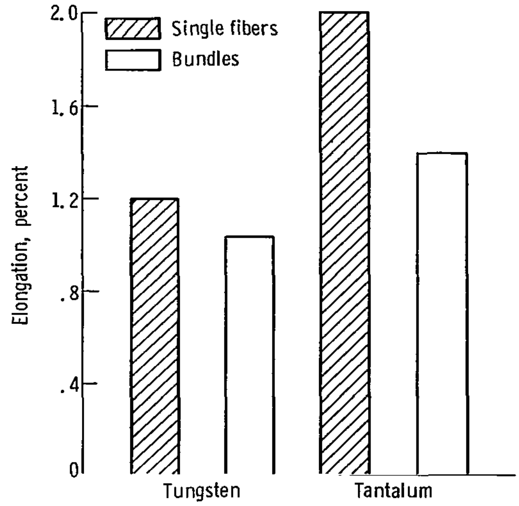


Figure 7. - Comparison of percentage of elongation values for single fibers and bundles of tantalum and tungsten.

the weakest fiber strength. Tantalum fibers are not sensitive to slight variations in fiber length because of their greater ductility.

The bundle tensile tests were performed so as to permit an additional comparison of bundle-fiber strength data with single-fiber data. As indicated in the procedure, the tensile-testing machine recorded the reduced load carried by the remaining fibers after each fiber failure. The data so collected permit a comparison of the strengths obtained for the surviving tantalum and tungsten fibers, tested in bundles of 10 each, with the data from the 10 tantalum and 10 tungsten fibers tested individually. The strengths of surviving fibers tested in bundles are shown in tables III and IV. The average strength for surviving tungsten and tantalum wires from bundle data was 261 000 and 121 000 psi (1800×10^6 and 834×10^6 N/m^2), respectively. These data compare with 271 000 and 119 000 psi (1868×10^6 and 820×10^6 N/m^2) for the tungsten and tantalum wires tested individually. The disparity in the tungsten data and the similarity in the tantalum data are similar to the observations discussed for the first-fiber-failure data. The more brittle tungsten wires were more sensitive to small inaccuracies in load application and fell below the single-fiber data. The tantalum data were in agreement within scatter. As in the single-fiber comparisons, the greater ductility of the tantalum overcame the minor inaccuracies of loading. These data indicate the extreme difficulty of experimentally verifying statistical treatments of brittle-single-fiber data.

In this study the strength of bundles containing mixtures of tantalum and tungsten fibers followed the rule of mixtures in agreement with Tsai (ref. 1). It appears component-fiber bundle strengths should be used to obtain a straight-line relation between bundle strength and percentage of fiber content of components in mixed-fiber bundles. However,

when single-fiber strength agrees with the bundle strength of a given fiber, as was the case with the tantalum fibers, single-fiber strength data can be used to predict the strength of that fiber in mixed-fiber bundles.

SUMMARY OF RESULTS

In this investigation of the tensile properties of tungsten and tantalum 10-fiber bundles and the relation of these properties to single-fiber strength, the following results were obtained:

1. The measured mean breaking stress of tungsten bundles was low compared with the mean strength of individual fibers. Bundles of 10 tungsten fibers broke at a mean breaking stress approximately 11 percent lower than the mean fiber strength as determined by separate tests on individual fibers (e.g., 240 000 psi (1655×10^6 N/m^2) for bundles as related to 271 000 psi (1868×10^6 N/m^2) for single fibers). Mean breaking stress for bundles is defined as the maximum load when the first fiber breaks divided by the total original fiber area.

2. Tantalum-fiber bundles had approximately the same mean strength as single tantalum fibers (116 000 psi (800×10^6 N/m^2) as related to 119 000 psi (820×10^6 N/m^2) for bundles). Monofilament tantalum fibers showed slightly more elongation than monofilament tungsten fibers. This additional elongation appeared to be enough to permit tantalum bundle strengths to agree with monofilament tantalum-fiber strength.

3. A calculation was performed which predicted the mean strength of the weakest fiber in tungsten bundles. The weakest-fiber strength was predicted from a statistical model based on the Weibull distribution (see appendix B) which used the single-fiber data. The strength value calculated for tungsten, 254 000 psi (1751×10^6 N/m^2), was high relative to the mean breaking stress for tungsten bundles, 240 000 psi (1655×10^6 N/m^2). This strength difference is probably due to slight inaccuracies in experimental technique which prevented perfect loading of the bundles. The predicted value for the tantalum bundle, 112 000 psi (772×10^6 N/m^2), was lower than the measured value, 116 000 psi (800×10^6 N/m^2).

4. A statistical study indicated the mean breaking stress and the volume percentage data conformed to the rule of mixtures for bundles containing mixtures of tantalum and tungsten fibers.

CONCLUDING REMARKS

Bundles made from strong, brittle fibers frequently display large variations in

strength. It is difficult to obtain full utilization of fiber strength potentials because of premature breakage of weaker fibers in bundles. Breakage might occur because some fibers have more flaws and are inherently weak or because completely uniform loading is difficult to obtain in practice. That is, some parts of a bundle can be loaded to fracture before the load can be uniformly distributed. In this study monofilament tantalum fibers showed slightly more elongation than monofilament tungsten fibers. This additional elongation appeared to be enough to permit tantalum bundle strengths to agree with monofilament tantalum-fiber strengths. The improvement in bundle strength as a result of slightly more elongation on the part of the fibers indicates a way to obtain higher strengths in bundles. Another way to improve the strength of bundles is to bond the bundle fibers together with a ductile matrix material. Work on copper-tungsten fiber composites at the Lewis Research Center showed that the composite strengths extrapolated directly to the strength of individual tungsten fibers (ref. 8). The ultimate strength level of a bonded bundle is not determined by the weakest fibers in the bundle. It is determined by averaging all the individual fiber strengths. Fracture of a few fibers in a composite containing many fibers has little effect on the composite strength because there are so many fibers still bearing a load. Even broken fiber segments are still able to support a load if the segments remain larger than the critical length (ref. 6).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 20, 1968,
129-03-09-01-22.

APPENDIX A

OBTAINING WEIBULL PARAMETERS FROM EXPERIMENTAL DATA

Consider that fibers in a bundle are characterized by a strength distribution of the Weibull type (ref. 2). If $\bar{l}$ is the mean fiber breaking load and $b(l)dl$ is the probability that a fiber breaks in a range of load from l to $(l + dl)$, then

$$\bar{l} = \int_0^{\infty} l\, b(l) dl \tag{1}$$

It can be shown that

$$\bar{l} = l_o \left(\frac{1}{n}\right)! \tag{2}$$

where l_o and n are the Weibull constants.

If s_l^2 is the variance of the mean fiber strength, then

$$s_l^2 = \int_0^{\infty} (l - \bar{l})^2\, b(l) dl \tag{3}$$

or

$$s_l^2 = l_o^2 \left\{\left(\frac{2}{n}\right)! - \left[\left(\frac{1}{n}\right)!\right]^2\right\} \tag{4}$$

The Weibull parameters, n and l_o, can be obtained from the experimental data by computing the numerical values of $\bar{l}$ and s_l^2 and substituting appropriate values in the identity,

$$\frac{s_l^2}{(\bar{l})^2} = \frac{\left(\frac{2}{n}\right)!}{\left[\left(\frac{1}{n}\right)!\right]^2} - 1 \tag{5}$$

Values of n can be obtained from this expression by trial substitutions, and l_o can then be obtained from equation (2), or

$$l_o = \frac{\bar{l}}{\left(\frac{1}{n}\right)!} \tag{6}$$

Corresponding stress values can be obtained from knowledge of the fiber cross-sectional area. Figure 8 shows the Weibull plot for the tungsten fibers used in this investigation, where $R(l)$ is the probability that a fiber will not break under a load l.

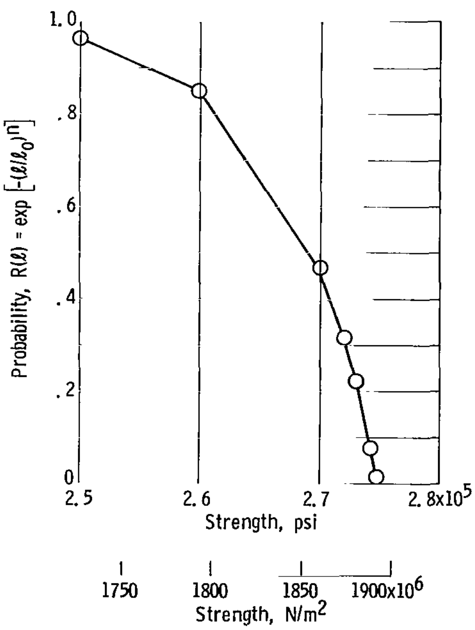


Figure 8. - Probability of fiber having given strength without breaking for tungsten fibers with Weibull constants, $\ell_0 = 2.75\times10^5$ and $n = 34.25$.

APPENDIX B

FINDING AVERAGE STRENGTH OF WEAKEST FIBERS IN BUNDLE OF q FIBERS

If u is the strength of the weakest fiber in a q-fiber bundle, f(u)du is the probability that u lies in du at u. The probability that a fiber will support a load of l without breaking is

$$R(l) = \exp\left[-\left(\frac{l}{l_o}\right)^n\right]$$

which is the Weibull distribution (ref. 2).

Where $B(l) = 1 - R(l)$ is the probability that a fiber will break under a load l and $B(l)dl$ is the probability that a fiber will break in a load range from l to $(l + dl)$, it is apparent that

$$B(l) = \int_0^l b(l)dl$$

and

$$f(u)du = qb(u)du\left[\int_u^\infty b(u)du\right]^{q-1}$$

$$\bar{u} = \frac{\bar{l}}{q^{1/n}} \tag{7}$$

where $\bar{u}$ is the average strength of the weakest fibers.

In the same manner it can be shown that the standard deviation of the strength of the weakest fibers out of a bundle of q fibers is equal to $s_l/q^{1/n}$ or

$$s_u = \frac{s_l}{q^{1/n}}$$

When the experimental values for tungsten fibers from table I are substituted in this expression, $\bar{u}$ is 254 000 psi (1751×10^6 N/m^2) with a standard deviation of 9054 psi (62.4×10^6 N/m^2). The average weakest fiber strength for tantalum fibers is 112 000 psi (772×10^6 N/m^2).

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TABLE I. - SUMMARY OF STATISTICAL DATA

[Weibull constants W: $n = 34.25$, $l_0 = 2.75\times10^5$; Ta: $n = 34.45$, $l_0 = 1.21\times10^5$]

Specimen	Parameters (a)	Breaking strength, psi	Breaking strength, N/m^2	Elongation, percent
10 Single Ta wires	$\overline{X}$	1.19×10^5	820.0×10^6	2.05
	S^2	1.78×10^7	846.8×10^{12}	
	S	4.22×10^3	29.1×10^6	
	V	3.55	-----------	
10 Bundles of 10 Ta wires each	$\overline{X}$	1.16×10^5	800.0×10^6	1.38
	S^2	2.24×10^7	1063.0×10^{12}	
	S	4.73×10^3	32.6×10^6	
	V	4.08	-----------	
10 Bundles, 20 vol. % W-Ta	$\overline{X}$	1.43×10^5	985.0×10^6	1.45
	S^2	5.7×10^7	2710.0×10^{12}	
	S	7.55×10^3	52.0×10^6	
	V	5.28	-----------	
10 Bundles, 50 vol. % W-Ta	$\overline{X}$	1.85×10^5	1275.0×10^6	1.24
	S^2	10.1×10^7	4740.0×10^{12}	
	S	10×10^3	68.9×10^6	
	V	5.4	-----------	
10 Bundles, 80 vol. % W-Ta	$\overline{X}$	2.14×10^5	1475.0×10^6	1.28
	S^2	18.3×10^7	8650.0×10^{12}	
	S	13.5×10^3	93.0×10^6	
	V	6.32	-----------	
10 Bundles of 10 W wires each	$\overline{X}$	2.40×10^5	1655.0×10^6	1.04
	S^2	13.5×10^7	6400.0×10^{12}	
	S	11.6×10^3	80.0×10^6	
	V	4.85	-----------	
10 Single W fibers	$\overline{X}$	2.71×10^5	1868.0×10^6	1.20
	S^2	9.34×10^7	4440.0×10^{12}	
	S	9.67×10^3	66.6×10^6	
	V	3.57	-----------	

[a]$\overline{X}$, mean value; S^2, variance; S, standard deviation; V, coefficient of variation, percent

TABLE II. - BREAKING STRENGTHS OF SINGLE FIBERS AND 10-FIBER BUNDLES

Breaking strength		Elongation, percent	Breaking strength		Elongation, percent	Breaking strength		Elongation, percent
psi	N/m^2		psi	N/m^2		psi	N/m^2	
Single Ta fibers			50 vol. % W-Ta bundles			W bundles (of 10 W fibers)		
117×10^3	806×10^6	2.05	173×10^3	1192×10^6	1.15	234×10^3	1612×10^6	1.05
117	806	1.85	188	1295	1.90	234	1612	1.30
127	875	1.55	193	1330	1.65	260	1793	1.05
122	840	2.45	188	1295	1.40	244	1682	.80
122	840	1.85	173	1192	.95	239	1647	.95
117	806	2.45	173	1192	.70	254	1751	1.30
117	806	2.30	188	1295	.90	244	1682	1.05
112	772	2.35	178	1227	1.45	224	1543	.80
122	840	2.40	198	1364	1.40	224	1543	1.20
117	806	1.05	198	1364	.90	239	1647	.85
Ta bundles (of 10 Ta fibers)			80 vol. % W-Ta bundles			Single W fibers		
122×10^3	840×10^6	1.55	224×10^3	1543×10^6	1.75	270×10^3	1861×10^6	1.25
112	772	1.25	209	1440	1.35	265	1828	1.05
122	840	1.10	224	1543	1.70	260	1793	.85
112	772	1.35	214	1474	1.35	270	1861	1.55
117	806	1.35	239	1647	1.65	280	1931	1.20
122	840	1.55	198	1364	.90	280	1931	1.50
112	772	1.30	198	1364	1.20	260	1793	1.00
112	772	1.20	214	1474	.85	260	1793	.75
112	772	1.10	198	1364	1.05	285	1966	1.45
112	772	1.50	219	1510	.95	280	1931	1.60
20 vol. % W-Ta bundles								
147×10^3	1013×10^6	1.35						
137	944	1.35						
153	1055	1.80						
142	979	1.65						
142	979	1.45						
153	1055	1.80						
142	979	1.40						
142	979	1.75						
142	979	1.00						
127	875	1.00						

TABLE III. - STRENGTHS OF FIBER BUNDLES OF TUNGSTEN

(a) Sequential breaking strengths for surviving fibers in tungsten bundles

Bundle	Number of fibers	Load per fiber, lb	Load per fiber, N	Mean strength per fiber, psi	Mean strength per fiber, N/m^2	Bundle	Number of fibers	Load per fiber, lb	Load per fiber, N	Mean strength per fiber, psi	Mean strength per fiber, N/m^2
1	10	4.67	20.80	238×10^3	1640×10^6	6	10	5.09	22.65	259×10^3	1786×10^6
	9	4.65	20.70	237	1633		9	4.82	21.40	245	1689
	8	4.69	20.85	238	1640		8	4.90	21.80	250	1725
	7	5.06	22.50	257	1772		7	5.17	23.00	263	1814
	6	4.80	21.35	244	1682		6	5.00	22.25	254	1751
	5	4.84	21.50	246	1697		5	5.09	22.65	259	1786
	4	5.21	23.20	265	1828		4	5.00	22.25	254	1751
	3	5.29	23.55	269	1854		3	5.00	22.25	254	1751
	2	5.00	22.25	254	1751		2	5.00	22.25	254	1751
	1	4.59	20.40	233	1605		1	5.84	26.00	297	2050
Mean				248×10^3	1711×10^6	Mean				259×10^3	1786×10^6
2	10	4.75	21.10	242×10^3	1668×10^6	7	10	4.88	21.70	248×10^3	1711×10^6
	9	5.06	22.50	258	1779		9	----	-----	-------	--------
	8	5.31	23.60	270	1861		8	----	-----	-------	--------
	7	----	-----	-------	--------		7	----	-----	-------	--------
	6	4.94	22.00	251	1731		6	----	-----	-------	--------
	5	5.34	23.80	271	1868		5	5.67	25.20	289	1990
	4	5.41	24.05	276	1903		4	6.05	26.90	308	2120
	3	----	-----	-------	--------		3	6.11	27.20	311	2140
	2	4.59	20.40	233	1605		2	6.89	30.60	350	2410
	1	5.00	22.25	254	1751		1	6.66	29.70	340	2340
Mean				257×10^3	1772×10^6	Mean				284×10^3	1959×10^6
3	10	5.21	23.20	265×10^3	1828×10^6	8	10	4.46	19.85	227×10^3	1565×10^6
	9	5.37	23.90	273	1882		9	4.45	19.80	226	1558
	8	5.11	22.75	260	1793		8	4.90	21.80	249	1718
	7	----	-----	-------	--------		7	4.83	21.45	246	1697
	6	5.21	23.20	265	1828		6	5.00	22.25	254	1751
	5	----	-----	-------	--------		5	4.84	21.50	246	1697
	4	----	-----	-------	--------		4	4.80	21.35	244	1682
	3	5.29	23.55	269	1854		3	4.72	21.00	240	1655
	2	5.41	24.05	276	1903		2	4.59	20.45	233	1605
	1	5.84	26.00	297	2050		1	5.00	22.25	254	1751
Mean				272×10^3	1875×10^6	Mean				242×10^3	1668×10^6
4	10	4.71	20.95	240×10^3	1655×10^6	9	10	4.34	19.35	221×10^3	1522×10^6
	9	5.10	22.70	259	1786		9	4.91	21.85	250	1725
	8	----	-----	-------	--------		8	----	-----	-------	--------
	7	5.06	22.50	258	1779		7	5.12	22.75	261	1800
	6	----	-----	-------	--------		6	5.07	22.55	258	1779
	5	5.25	23.35	267	1841		5	5.00	22.25	254	1751
	4	5.10	22.70	259	1786		4	----	-----	-------	--------
	3	5.29	23.55	269	1854		3	5.00	22.25	254	1751
	2	5.84	26.00	297	2050		2	5.42	24.10	276	1903
	1	5.42	24.10	276	1903		1	5.84	26.00	297	2050
Mean				266×10^3	1835×10^6	Mean				259×10^3	1786×10^6
5	10	4.75	21.10	242×10^3	1668×10^6	10	10	4.84	21.50	246×10^3	1697×10^6
	9	4.82	21.40	245	1689		9	5.00	22.25	254	1751
	8	5.07	22.55	258	1779		8	----	-----	-------	--------
	7	5.17	23.00	263	1814		7	5.12	22.75	260	1793
	6	5.07	22.55	258	1779		6	5.15	22.90	262	1807
	5	5.00	22.25	254	1751		5	5.16	22.95	263	1814
	4	5.21	23.20	266	1835		4	5.42	24.10	276	1903
	3	4.86	21.60	247	1704		3	5.28	23.50	268	1847
	2	5.00	22.25	254	1751		2	5.42	24.10	276	1903
	1	5.84	26.00	297	2050		1	----	-----	-------	--------
Mean				258×10^3	1779×10^6	Mean				264×10^3	1821×10^6

TABLE III. - Concluded. STRENGTHS OF FIBER BUNDLES OF TUNGSTEN

(b) Strengths of fiber bundles grouped according to number of fibers surviving

Fibers surviving in bundle	Bundle strength	
	psi	N/m^2
10	238×10^3	1640×10^6
	242	1668
	265	1828
	240	1655
	242	1668
	259	1786
	248	1711
	227	1565
	221	1522
	246	1697
Mean	243×10^3	1675×10^6
9	237×10^3	1633×10^6
	258	1779
	273	1882
	259	1786
	245	1689
	245	1689
	226	1558
	250	1725
	254	1751
Mean	250×10^3	1725×10^6
8	238×10^3	1640×10^6
	270	1861
	260	1793
	258	1779
	250	1725
	249	1718
Mean	254×10^3	1751×10^6
7	258×10^3	1779×10^6
	258	1779
	263	1814
	263	1814
	246	1697
	261	1800
	260	1793
Mean	258×10^3	1779×10^6

Fibers surviving in bundle	Bundle strength	
	psi	N/m^2
6	244×10^3	1682×10^6
	251	1731
	265	1828
	258	1779
	254	1751
	254	1751
	258	1779
	262	1807
Mean	257×10^3	1772×10^6
5	246×10^3	1697×10^6
	271	1868
	267	1841
	254	1751
	259	1786
	289	1990
	246	1697
	254	1751
	263	1814
Mean	261×10^3	1800×10^6
4	265×10^3	1828×10^6
	276	1903
	259	1786
	266	1835
	254	1751
	308	2120
	244	1682
	276	1903
Mean	269×10^3	1854×10^6
3	269×10^3	1854×10^6
	269	1854
	269	1854
	247	1704
	254	1751
	311	2140
	240	1655
	254	1751
	268	1847
Mean	275×10^3	1896×10^6

Fibers surviving in bundle	Bundle strength	
	psi	N/m^2
2	254×10^3	1751×10^6
	233	1605
	276	1903
	297	2050
	254	1751
	254	1751
	350	2410
	233	1605
	276	1903
	276	1903
Mean	270×10^3	1861×10^6
1	233×10^3	1605×10^6
	254	1751
	297	2050
	276	1903
	297	2050
	297	2050
	340	2340
	254	1751
	297	2050
Mean	283×10^3	1952×10^6

TABLE IV. - STRENGTHS OF FIBER BUNDLES OF TANTALUM

(a) Sequential breaking strengths for surviving fibers in tantalum bundles

Bundle	Number of fibers	Load per fiber, lb	Load per fiber, N	Mean strength per fiber, psi	Mean strength per fiber, N/m^2
1	10	2.46	10.95	125×10^3	861×10^6
	9	2.50	11.10	127	875
	8	2.61	11.60	133	916
	7	2.68	11.90	136	938
	6	2.64	11.75	134	924
	5	2.75	12.25	140	965
	4	----	-----	-------	-------
	3	2.64	11.75	134	924
	2	----	-----	-------	-------
	1	3.34	14.85	170	1170
Mean				139×10^3	959×10^6
2	10	2.17	9.65	110×10^3	758×10^6
	9	2.04	9.10	104	717
	8	2.04	9.10	104	717
	7	2.03	9.05	103	710
	6	2.08	9.25	106	730
	5	2.00	8.90	102	704
	4	1.99	8.85	101	696
	3	1.80	8.00	92	634
	2	1.67	7.45	85	586
	1	----	----	-------	-------
Mean				101×10^3	696×10^6
3	10	2.38	10.60	121×10^3	834×10^6
	9	2.50	11.10	127	875
	8	2.50	11.10	127	875
	7	2.50	11.10	127	875
	6	2.57	11.45	131	904
	5	----	-----	-------	-------
	4	----	-----	-------	-------
	3	2.36	10.50	120	827
	2	2.50	11.10	127	875
	1	2.92	13.00	148	1020
Mean				129×10^3	889×10^6
4	10	2.25	10.00	115×10^3	793×10^6
	9	2.32	10.30	118	813
	8	2.40	10.70	122	840
	7	2.56	11.40	130	896
	6	2.64	11.75	134	924
	5	2.58	11.50	131	904
	4	2.61	11.60	133	916
	3	2.50	11.10	127	875
	2	2.71	12.05	138	951
	1	----	-----	-------	-------
Mean				127×10^3	875×10^6
5	10	2.29	10.20	116×10^3	800×10^6
	9	2.13	9.50	108	800
	8	2.19	9.75	111	765
	7	2.08	9.25	106	730
	6	2.08	9.25	106	730
	5	2.00	8.90	102	704
	4	2.08	9.25	106	730
	3	----	----	-------	-------
	2	2.08	9.25	106	730
	1	2.08	9.25	106	730
Mean				107×10^3	737×10^6
6	10	2.42	10.75	123×10^3	849×10^6
	9	2.50	11.10	127	875
	8	2.61	11.60	133	916
	7	2.62	11.65	133	916
	6	2.64	11.75	134	924
	5	2.75	12.25	140	965
	4	2.81	12.50	143	985
	3	2.64	11.75	134	924
	2	----	-----	------	-------
	1	2.50	11.10	127	875
Mean				133×10^3	916×10^6
7	10	2.25	10.00	115×10^3	793×10^6
	9	2.41	10.70	123	849
	8	2.55	11.35	130	896
	7	2.44	10.85	124	855
	6	----	-----	-------	-------
	5	3.17	14.10	161	1110
	4	----	-----	-------	--------
	3	2.64	11.75	134	924
	2	2.71	12.05	138	951
	1	2.92	13.00	148	1020
Mean				134×10^3	924×10^6
8	10	2.21	9.85	112×10^3	772×10^6
	9	2.37	10.55	121	834
	8	----	-----	-------	-------
	7	2.38	10.60	121	834
	6	----	-----	-------	-------
	5	2.42	10.75	123	849
	4	2.50	11.10	127	875
	3	----	-----	-------	-------
	2	----	-----	-------	-------
	1	2.50	11.10	127	875
Mean				122×10^3	840×10^6
9	10	2.13	9.50	108×10^3	744×10^6
	9	2.18	9.70	111	765
	8	2.20	9.80	112	772
	7	2.20	9.80	112	772
	6	2.23	9.95	113	779
	5	2.17	9.65	110	758
	4	2.09	9.30	106	730
	3	2.36	10.50	120	827
	2	2.50	11.10	127	875
	1	2.92	13.00	148	1020
Mean				117×10^3	806×10^6
10	10	2.21	9.85	113×10^3	779×10^6
	9	2.32	10.30	118	813
	8	2.18	9.70	111	765
	7	2.20	9.80	112	772
	6	2.29	10.20	116	800
	5	2.00	8.90	102	704
	4	1.88	8.35	96	662
	3	1.80	8.00	92	634
	2	----	-----	-------	-------
	1	----	-----	-------	-------
Mean				107×10^3	737×10^6

TABLE IV. - Concluded. STRENGTHS OF FIBER BUNDLES OF TANTALUM

(b) Strengths of fiber bundles grouped according to number of fibers surviving

Fibers surviving in bundle	Breaking strength, psi	Breaking strength, N/m^2	Fibers surviving in bundle	Breaking strength, psi	Breaking strength, N/m^2	Fibers surviving in bundle	Breaking strength, psi	Breaking strength, N/m^2
10	125×10^{3}	861×10^{6}	6	134×10^{3}	924×10^{6}	2	85×10^{3}	586×10^{6}
	110	758		106	730		127	875
	121	834		131	904		138	951
	115	793		134	924		106	730
	116	800		106	730		138	951
	123	849		134	924		127	875
	115	793		113	779			
	112	772		116	800			
	108	744						
	113	779						
Mean	116×10^{3}	800×10^{6}	Mean	122×10^{3}	840×10^{6}	Mean	120×10^{3}	827×10^{6}
9	127×10^{3}	875×10^{6}	5	140×10^{3}	965×10^{6}	1	170×10^{3}	1170×10^{6}
	104	717		102	704		148	1020
	127	875		131	904		106	730
	118	813		102	704		127	875
	108	744		140	965		148	1020
	127	875		161	1110		127	875
	123	849		123	849		148	1020
	121	834		110	758			
	111	765		102	704			
	118	813						
Mean	118×10^{3}	813×10^{6}	Mean	124×10^{3}	855×10^{6}	Mean	139×10^{3}	958×10^{6}
8	133×10^{3}	916×10^{6}	4	101×10^{3}	696×10^{6}			
	104	717		133	916			
	127	875		106	730			
	122	840		143	985			
	111	765		127	875			
	133	916		106	730			
	130	896		96	662			
	112	772						
	111	765						
Mean	120×10^{3}	827×10^{6}	Mean	116×10^{3}	800×10^{6}			
7	136×10^{3}	938×10^{6}	3	134×10^{3}	924×10^{6}			
	103	710		92	634			
	127	875		120	827			
	130	896		127	875			
	106	730		134	924			
	133	916		134	924			
	124	855		120	827			
	121	834		92	634			
	112	772						
	112	772						
Mean	120×10^{3}	827×10^{6}	Mean	119×10^{3}	820×10^{6}			

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